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Torsion Gelometry of Cheese[1]

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ABSTRACT

Torsion gelometry, a fundamental rheological test in which specimens are twisted until they fracture, was applied to several different cheese varieties to determine its suitability for measuring their textural properties. Fresh and aged Brick, Cheddar, Colby, Gouda, Havarti, Mozzarella, and Romano cheeses were subjected to torsion analysis, and the results were compared with those from small amplitude oscillatory shear (SAOS) tests and texture profile analysis (TPA). Strong relationships (correlation coefficients > 0.8) were found between torsion shear stress and TPA hardness, and between torsion shear strain and TPA cohesiveness. SAOS, which measures rheological properties of intact samples, did not correlate well with torsion or TPA. A map showing trends during aging toward brittle, mushy, rubbery, and tough texture was drawn using the torsion data. The findings show that torsion gelometry provides fundamental rheological data on cheese at the fracture point. The information can be used to compare textural qualities of cheese samples as they are being cut.
(**Key words:** cheese, oscillatory shear, texture profile analysis, torsion gelometry)

Abbreviation key: **G′** = storage modulus, **G″** = loss modulus, **G*** = complex modulus, η^* = complex viscosity, σ_{max} = torsion shear stress at failure, γ_{max} = torsion shear strain at failure, **MNFS** = moisture in nonfat substance, **SAOS** = small amplitude oscillatory shear, **TPA** = texture profile analysis.

INTRODUCTION

The three categories of food texture measurement are empirical, imitative, and fundamental tests (Scott Blair, 1958). Empirical tests involve test conditions that cannot usually be compared with those of more rigorous experiments. Imitative tests such as texture profile analysis (**TPA**) utilize a universal testing machine to mimic chewing; these tests can also be considered empirical, as there are no corrections for changes in the shape of the specimen. TPA is useful for making comparisons, but does not measure true rheological properties. Fundamental tests, such as small amplitude oscillatory shear (**SAOS**), use specific specimen geometries and instruments, allowing systematic analysis of the results. Stress and strain are linearly dependent on each other and the sample does not fracture or change shape in SAOS tests, which provide data on viscoelastic properties including storage modulus (**G′**), loss modulus (**G″**), and complex viscosity (η^*) (Tunick, 2000).

Another fundamental test, torsion gelometry, was developed for use on food gels at North Carolina State University (Diehl et al., 1979). In a torsion test, specimens are twisted in a viscometer, with the shear stress (σ_{max}) and shear strain (γ_{max}) being measured at the fracture point. In analysis of cheese, specimens are milled into a capstan shape so that the fracture takes place at the narrow center of the specimen. Fracture can occur in compression, shear, or tension mode, which are imposed at equal magnitudes in different directions (Hamann and Foegeding, 1994). Torsion gelometry has been used to analyze a number of foods and food gels (Hamann, 1983) and has been correlated with sensory ratings by a texture profile panel (Montejano et al., 1986; Gwartney et al., 2002). A comparison of torsion gelometry, TPA, and sensory texture of various gels showed that the highest correlations among instrumental parameters were observed between shear stress and TPA hardness, and shear strain and TPA cohesiveness (Montejano et al., 1986). Torsion gelometry is gaining more widespread use because improvements in the technique have reduced the difficulties previously involved in sample preparation and analysis. Torsion gelometry has recently been applied to cheese (Foegeding et al., 1998) and was compared to vane rheometry in tests on Cheddar, Mozzarella, and processed cheeses (Truong and Daubert, 2001). Their results indicated that Cheddar, the hardest cheese they tested, exhibited the highest shear stress; and Mozzarella, the most elastic cheese in their experiments, exhibited the highest

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shear strain. Another study compared torsion gelometry of low- and full-fat Monterey Jack, Cheddar, and American cheeses to texture scores from a sensory panel (Gwartney et al., 2002). Fracture stress and strain were each significantly correlated with several sensory descriptors. These are the only cheese varieties that have been analyzed by torsion gelometry and reported in the literature.

A comparison of torsion gelometry, TPA, and SAOS rheology was recently performed on Mozzarella cheeses in our laboratory (Tunick et al., 2000). Since torsion gelometry measures fundamental rheological properties at the fracture point, it should prove valuable in analyzing cheese samples as they are being broken apart, such as when the consumer cuts or bites into them. Cheese production in the U.S. has been increasing for years, reaching 3.75×10^9 kg in 2000 (USDA, 2001), so reliable methods for characterizing the texture of this product will be important for those in the cheese industry. The object of this study was to develop torsion data for a variety of cheeses, and to compare the results with an imitative test (TPA) and another fundamental test (SAOS).

MATERIALS AND METHODS

Commercial cheeses were manufactured at the University of Wisconsin and shipped under refrigeration overnight. Cheese varieties consisted of fresh and aged Brick, Colby, Gouda, Havarti, and Romano; fresh, mild, medium, and sharp Cheddar; and Old Amsterdam, which is Gouda aged without the wax coating after 18 mo. The ages at analysis of the aged cheeses were above the minimums specified by the US Federal Standards of Identity (Table 1). Low moisture part skim Mozzarella cheeses prepared in our laboratory in a previous study (Tunick et al., 2000) were also included. There was one sample each of the fresh Brick, Havarti, and Romano, and two samples of each of the other cheeses.

Moisture content was determined by the forced draft oven method (AOAC International, 1997) and fat content by the modified Babcock test (Kosikowski and Mistry, 1997b). Moisture in nonfat substance (MNFS) was calculated as $100\% \times (\%\ \text{moisture})/(100 - \%\ \text{fat})$.

Rheological tests were conducted at 20–22°C. TPA was performed as previously described (Tunick et al., 1991). Four cylinders measuring approximately 15 mm in diameter and 15 mm in height were cut from the samples and each was compressed twice by 75% in a Sintech 1/G universal testing machine (MTS Systems, Eden Prairie, MN) operating at a crosshead speed of 100 cm/min. Hardness, springiness, and cohesiveness were calculated by the instrument's software from the resulting force-distance curve, and these values were multiplied by each other to obtain chewiness values (Tunick, 2000). SAOS measurements were made as previously described (Tunick et al., 1990), with G′, G″, and η^* being determined in triplicate with a Rheometrics Dynamic Analyzer model RDA-700 (Rheometrics Scientific, Piscataway, NJ) at a frequency of 10 rad/s.

Shear stress and shear strain values at point of fracture were determined in a torsion gelometer (Gel Consultants, Raleigh, NC) operating at 2.5 rpm. Four plugs were bored from the sample and milled to the appropriate capstan shape as described by Foegeding (1992). A specific milling configuration was used to insure that the specimens were uniform so that their geometry had minimal influence on the calculations. Shear rigidity, which is $\sigma_{\max}/\gamma_{\max}$, was also calculated.

The SAS Software System (SAS Institute, 1999) was used to obtain Pearson correlations and standard errors. A correlation is described as significant if $P < 0.05$.

RESULTS AND DISCUSSION

Composition

Table 1 shows the varieties, ages, and compositions of the cheeses. The varieties included two surface ripened cheeses (Brick and Havarti), a pasta filata type (Mozzarella), three hard cheeses (Cheddar, Colby, and Gouda), and two varieties that become very hard with age (Old Amsterdam and Romano). The moisture contents of the aged Colby and Havarti cheeses were slightly higher than those specified in the Standards of Identity, but the moisture levels of the other cheeses and all of the fat levels were within the Standards. The cheeses in this study were selected in part because of their dissimilar compositions: the moisture levels were between 33.7 and 51.6%, and the fat levels were between 18.1 and 36.0%. The Romano became drier with storage, but the moisture and fat content of the other cheeses did not change appreciably. MNFS, which is essentially a ratio of water to protein and is related to firmness (Olson and Johnson, 1990), is also included and will be discussed later.

Rheological Results

Table 2 shows the rheological data. In the torsion results, the values for $\sigma_{\max}$ and $\gamma_{\max}$ were calculated by the following equations, where K = shape factor constant = 1.08, r = minimum sample radius = 5 mm, M = torque (N cm), ϕ = angular deformation of the curved section (rad), and Q = constant for the curved section = 8.45×10^{-6} m^{-3} (Diehl et al., 1979):

$$\sigma_{\max} = \frac{2KM}{\pi r^3}$$

Table 1. Average age and composition of cheese varieties tested, compared with US Federal Standards of Identity.

	This study				Standards of identity[1]		
Variety	Age	Moisture	Fat	MNFS[2]	Minimum age	Maximum moisture	Minimum fat
	(d)	(%)			(d)	(%)	
Brick, fresh	7	38.5	33.0	57.5			
Brick, aged	78	38.3	33.3	57.4	60	44	28.0
Cheddar, fresh	12	37.7	33.5	56.7			
Cheddar, mild	56	37.0	32.4	54.7			
Cheddar, medium	197	38.2	31.3	55.6			
Cheddar, sharp	379	36.3	34.8	55.7	60	39	30.5
Colby, fresh	10	39.7	31.7	58.1			
Colby, aged	202	40.5	30.8	58.5	60	40	30.0
Gouda, fresh	38	37.7	36.0	58.9			
Gouda, aged	154	40.4	32.0	59.4	a	45	25.3
Old Amsterdam	566	38.0	33.0	56.7			
Havarti, fresh	15	42.0	34.0	63.6			
Havarti, aged	113	42.0	34.3	63.9	a	39	22.6
Mozzarella, fresh	7	51.6	18.1	62.9			
Mozzarella, aged	42	51.6	18.1	62.9	a	52	14.4
Romano, fresh	34	36.3	26.6	49.5			
Romano, aged	505	33.7	27.3	46.4	150	34	25.1
SE		1.2	1.3	1.1			

[a]No minimum age requirement.

[1]Data from USFDA 2000.

[2]MNFS = Moisture in nonfat substance.

$$\gamma_{max} = \frac{2K\phi}{\pi r^3 Q}$$

Since shear stress is directly proportional to torque, the hardest cheeses, Romano and Old Amsterdam, had the highest values for σ_{max}, as well as the highest shear rigidity values. Truong and Daubert (2001) also found that σ_{max} was dependent on the hardness, with Cheddar > Mozzarella > processed cheese. Shear strain is dependent on angular deformation, and γ_{max} values for the Mozzarella are therefore high because Mozzarella is stretched during manufacture, which aligns the protein fibers and gives the cheese its characteristic deformability. This result is also in agreement with Truong and

Table 2. Torsion gelometry, texture profile analysis, and small amplitude oscillatory shear results for cheeses.

	Torsion			Texture profile analysis				Small amplitude oscillatory shear		
Variety	Shear stress (kPa)	Shear strain	Shear rigidity (kPa)	Hardness (N)	Springiness (mm)	Cohesiveness	Chewiness (mJ)	Elastic modulus (kPa)	Viscous modulus (kPa)	Complex viscosity (kPa·s)
Brick, fresh	55.9	1.33	42.0	88.6	8.64	0.27	207	35.4	13.3	3.78
Brick, aged	29.8	1.66	18.0	45.5	9.74	0.35	155	43.1	20.4	4.77
Cheddar, fresh	42.9	0.83	51.9	46.5	8.57	0.21	83.7	75.3	30.0	8.13
Cheddar, mild	53.4	1.28	41.7	46.4	9.13	0.21	89.0	77.2	32.4	8.38
Cheddar, medium	42.6	1.06	40.2	40.5	10.54	0.19	81.1	68.0	31.4	7.50
Cheddar, sharp	31.5	0.75	42.0	38.9	10.91	0.13	55.2	40.8	21.4	4.62
Colby, fresh	49.8	1.13	44.1	73.8	8.55	0.28	177	47.1	18.4	5.07
Colby, aged	32.0	1.26	25.4	48.6	8.44	0.25	103	40.6	19.4	4.52
Gouda, fresh	48.8	1.86	26.2	77.4	10.02	0.41	318	43.9	17.8	4.74
Gouda, aged	21.8	1.65	13.2	34.5	9.68	0.34	114	30.7	18.0	3.57
Old Amsterdam	98.1	0.44	223	96.4	11.44	0.11	121	83.7	38.7	9.29
Havarti, fresh	40.7	1.27	32.0	56.9	10.16	0.39	225	83.3	25.6	8.72
Havarti, aged	16.9	1.34	12.6	19.8	9.21	0.24	43.8	37.0	14.0	3.96
Mozzarella, fresh	48.5	1.56	31.1	68.0	9.70	0.41	270	35.9	13.6	3.83
Mozzarella, aged	25.7	1.85	13.9	49.0	9.83	0.62	299	27.4	9.3	2.98
Romano, fresh	99.0	0.92	108	168	6.42	0.17	183	48.1	18.4	5.16
Romano, aged	151.4	0.51	297	233	9.73	0.18	408	87.0	40.9	9.63
SE	8.3	0.04	7.5	5.7	0.12	0.01	11.6	3.1	1.5	0.34

Daubert (2001), who found that γ_{max} values for Mozzarella were higher than those for Cheddar or processed cheese. The cheeses in the torsion experiments fractured in the shear mode.

In TPA tests, specimens are subjected to uniaxial compression instead of angular deformation, causing failure of the specimen in the compression mode. TPA hardness is the maximum force during the first compression cycle, springiness is the height the sample recovers between the first and second compressions, and cohesiveness is the ratio of the positive force area of the second compression to that of the first (Tunick, 2000). These experiments showed that most of the cheeses became less hard and less cohesive with age; springiness did not display a significant trend. Proteolytic breakdown of α_{s1}-casein into peptides causes cheese to soften and lose structural integrity with time (Fox, 1989). Consequently, the values for chewiness, defined as the amount of work required to masticate a solid food sample, usually decreased with storage. The Romano and the Gouda/Old Amsterdam cheeses are intended to become drier and harder with age, and their values for σ_{max}, shear rigidity, hardness, and springiness increased with time. The cohesiveness of the Mozzarella, which has an elastic body, increased dramatically during storage as observed in previous experiments (Tunick et al., 1991). The cohesiveness of the Brick, which is also supposed to be elastic when ready for consumption (Olson, 1969), also increased. The aged Havarti had the lowest hardness and σ_{max}; its curds are suspended in diluted whey when salt is added, which partially solubilizes the protein and softens the structure (Kosikowski and Mistry, 1997a).

SAOS differs from torsion tests because stress and strain are varied harmonically with time at a frequency ω on intact specimens. G*, the complex modulus, is the ratio of the maximum stress to the maximum strain, and is the total energy required to deform the specimen. In purely elastic and in purely viscous samples, the strain and the resulting stress are out of phase by 0° and 90°, respectively. In viscoelastic substances such as cheese, the stress and strain are out of phase by an angle δ, which is between 0° and 90°. The storage modulus is a measure of the energy stored in a sample during a SAOS deformation cycle, the loss modulus is a measure of the energy lost as heat, and the complex viscosity provides information on viscoelastic flow (Tunick, 2000). These parameters are related to G* as follows:

$$G' = G^* \cos \delta$$
$$G'' = G^* \sin \delta$$
$$\eta^* = G^*/\omega$$

SAOS results on cheese samples are dependent on the number and strength of the bonds between the casein particles, the structure of those particles, and the spatial distribution of the strands making up those particles (Roefs et al., 1990). For instance, the G′, G″, and η^* values for the Colby samples were much smaller than those of the Cheddar samples of the same age. These cheeses are manufactured in a similar manner except that Colby curd is stirred and not cheddared. As a result, the curd particles in Colby do not knit as well as in Cheddar, leading to weaker interactions between the casein strands. The G′ value for the Havarti decreased greatly with age because air holes are incorporated between the curd grains in the manufacture of Havarti, and CO_2 production during ripening expands these holes (Nielsen, 1993). The SAOS results for all of the cheeses followed the same general trends as the torsion and TPA results, increasing with age for Gouda/Old Amsterdam and Romano and usually decreasing with age for the other varieties.

Correlations Between Methods

Table 3 shows correlations among the rheological and compositional parameters. Shear rigidity was strongly correlated with shear stress (coefficient of 0.899). Shear stress, which is the force required for fracture, also showed a strong positive correlation (0.859) with hardness, which measures the force needed to attain a given deformation. Montejano et al. (1986) observed the same result with their protein gel preparations, concluding that the two tests were similar in their ability to measure strength characteristics. Shear strain exhibited a strong positive correlation (0.818) with cohesiveness, a result also observed by Montejano et al. (1986). Both parameters reflect the deformability of a food. Shear rigidity, an indication of stiffness, showed a fairly strong positive correlation (0.713) with hardness but only a moderate negative correlation (–0.422) with cohesiveness. These results indicate that torsion gelometry provides a fundamental alternative to TPA in characterizing the texture of cheese.

The correlation coefficients between TPA springiness and the other instrumental parameters were all between –0.24 and 0.22. Springiness measures recovery after a specimen is compressed, and is not analogous to torsion or SAOS parameters. The correlation coefficients between cohesiveness, chewiness, and the SAOS parameters were all between –0.28 and 0.26. Chewiness is proportional to hardness, and the correlation coefficient between the two was 0.822.

G′, G″, and η^* were highly correlated with each other (> 0.88), but not with the other parameters. G″ had moderate correlations (between –0.41 and 0.51) with

Table 3. Pearson correlation coefficients[1] among composition, torsion gelometry, texture profile analysis, and small amplitude oscillatory shear (SAOS) data.

	Composition				Torsion			Texture profile analysis				SAOS	
	Age	Moisture	Fat	MNFS[2]	Shear stress	Shear strain	Shear rigidity	Hardness	Springiness	Cohesiveness	Chewiness	Storage modulus	Loss modulus
Shear stress	−0.453[3]	−0.717	−0.675	−0.805									
Shear strain	−0.552	0.502	0.427	0.553	−0.542								
Shear rigidity	0.431	−0.635	−0.551	−0.693	0.899	−0.660							
Hardness	−0.474[3]	−0.678	−0.739	−0.801	0.859	−0.358	0.713						
Springiness	0.476	−0.010	0.532	0.241	−0.046	−0.087	0.158	−0.115					
Cohesiveness	−0.535	0.513	0.396	0.555	−0.332	0.818	−0.422	−0.201	0.010				
Chewiness	0.193	−0.408	−0.306	−0.409	0.423	0.262	0.255	0.822	0.068	0.311			
Storage modulus	0.323	−0.331	−0.196	−0.323	0.338	−0.361	0.335	0.349	0.208	−0.212	0.253		
Loss modulus	0.388	−0.490	−0.209	−0.451	0.454	−0.414	0.505	0.323	−0.235	−0.276	0.186	0.883	
Complex viscosity	0.337	−0.361	−0.210	−0.352	0.368	−0.380	0.376	0.350	0.217	−0.227	0.246	0.996	0.920

[1]Correlation coefficients were significant at $P < 0.001$ (> 0.41 or < −0.41), $P < 0.01$ (> 0.32 or < −0.32), and $P < 0.05$ (> 0.23 or < −0.23).

[2]MNFS = Moisture in nonfat substance.

[3]Calculation excludes fresh and aged Romano, fresh Gouda, and Old Amsterdam. The correlation coefficients for those cheeses alone were 0.471 for shear stress/age and 0.449 for hardness/age.

the torsion values, but otherwise the SAOS parameters had correlations between −0.38 and 0.38 with the torsion and TPA values. SAOS yields information on short-range interactions of intact specimens, and is not useful in predicting behavior of cheese as it fractures.

Variations with MNFS

Moisture in nonfat substances (**MNFS**) has been cited as the most important variable affecting cheese quality (Pearce and Gilles, 1979). MNFS exhibited moderate positive correlations (both 0.55) with γ_{max} and cohesiveness, and strong negative correlations (both −0.80) with σ_{max} and hardness. MNFS showed weaker negative correlations (between −0.32 and −0.45) with chewiness, G′, G″, and η^*. The correlation with springiness was low. The casein in cheese becomes more hydrated as MNFS increases, which has been shown in Mozzarella to result in lower hardness, G′, G″, and η^* values (Tunick et al., 1993). σ_{max} and shear rigidity would be expected to decrease as well. Cohesiveness and γ_{max} were directly related to MNFS because casein hydration results in a more cohesive gel.

Comparisons of moisture with the torsion and TPA data produced lesser correlations than the corresponding comparisons with MNFS; the comparisons between moisture and the SAOS data produced slightly better correlations. Except for springiness, fat content did not correlate with the rheological data as well as MNFS. These results indicate that MNFS is a better predictor of texture than percentage of moisture or fat.

Variations with Storage Time

Storage time (age) exhibited moderate positive correlations with shear rigidity (0.431) and springiness (0.476), and moderate negative correlations with γ_{max} (−0.552) and cohesiveness (−0.535). The correlations with the SAOS parameters were lower (< 0.39). When only fresh and aged Romano, fresh Gouda, and Old Amsterdam were considered, the correlation coefficient between hardness and age was 0.449, and between σ_{max} and age was 0.471. As previously mentioned, these cheeses become drier and harder with storage. Among the other cheeses, which soften with time because of proteolysis, the correlation coefficient between hardness and age was −0.474, and between σ_{max} and age was −0.453.

Texture Map

A texture map, which is a plot of shear stress vs. shear strain, provides a graphical representation of product texture (Truong and Daubert, 2001). Maps illustrating

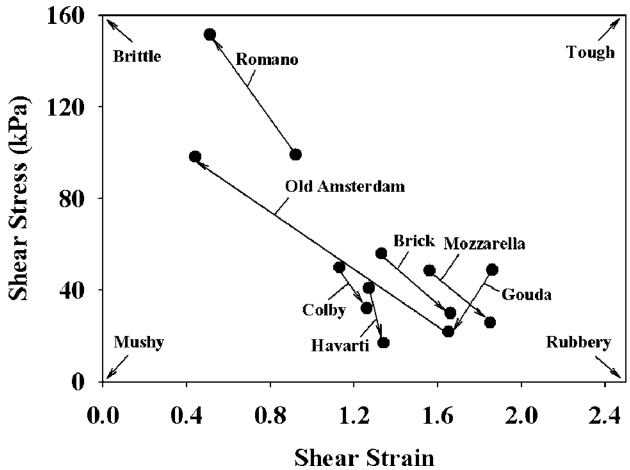

Figure 1. Texture map of commercial Brick, Colby, Gouda, Havarti, and Old Amsterdam cheeses. Part skim Mozzarella cheese from a previous study (Tunick et al., 2000) is also included. Arrows point from the fresh cheeses to the corresponding aged cheeses, indicating textural changes with storage.

the textural changes in the cheeses with age are shown in Figures 1 and 2. Foods exhibiting low σ_{max} are termed mushy if γ_{max} is low (a better descriptor for cheese would be "soft"), and rubbery if γ_{max} is high. Foods with high σ_{max} values can be considered brittle if γ_{max} is low, and tough if γ_{max} is high. The Romano and Old Amsterdam, which lost moisture with age, became much more brittle. The Gouda was softer after 5 mo aging; the Cheddar initially became tougher with age, but then became softer as proteolysis broke down the protein matrix (Figure 2). The Brick, Colby, Havarti, and Mozzarella all became more rubbery as they aged. The Brick and Mozzarella, the two relatively elastic varieties, showed a more pronounced change.

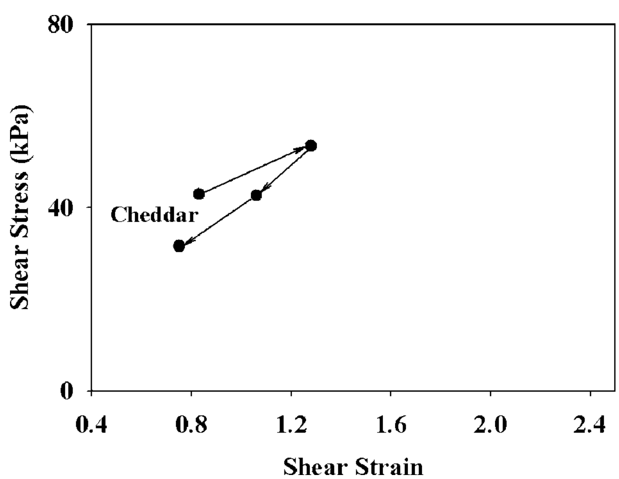

Figure 2. Texture map of commercial Cheddar cheese. Arrows point from fresh to mild to medium to sharp Cheddar.

Information from a texture map such as this one is useful to food scientists who wish to relate parameters such as aging and composition to stress and strain of the product at fracture. These mechanical properties are important to consumer perception, and torsion gelometry provides a systematic method of measuring them.

CONCLUSIONS

Torsion gelometry provides fundamental rheological data on cheese at the fracture point. Testing of a number of cheeses of different types and ages reveals that torsion shear stress is highly correlated with TPA hardness, and torsion shear strain with TPA cohesiveness. Torsion tests can be used to characterize textural attributes that are meaningful to food scientists and consumers.

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